# Survivability – An Information Fusion Process Metric from An Operational Perspective

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Abstract – ***This paper presents a new probabilistic approach to determine survivability of reconfigurable systems as a system-level performance metric in an operational environment. In contrast to known methods of estimating survivability in terms of susceptibility and vulnerability, the proposed method (1) includes directional threats on various subsystems into the analysis and (2) provides a framework for operational information fusion processes to better sustain unpredictable or hostile environmental disturbances. In this paper, we distinguish the survivability and reliability metrics, where we demonstrate the importance of survivability metric in a dynamic information fusion process for an operational environment. We present our main result using a piping system of fluid flow; however, the concept easily extends to other flow systems, such as power networks, computer communication networks, and military reconfigurable information systems, etc. Survivability of these large scale reconfigurable networks depend on their capability of assessing directional threats, situation awareness, and their ability to dynamically adapt to new configurations. The proposed survivability method embedded in an information fusion environment can be used for real time dynamic reconfiguration of large scale systems, optimization and routing of data and information, and detect and mitigate hardware and software threats.***

**Keywords:**. Survivability, reliability, fusion, situation awareness, situation assessment.

## 1 Introduction

In 1990, the US Department of Defense defined information fusion as '*a technology which involves the acquisition, integration, filtering, correlation and synthesis of useful data from diverse sources for the purposes of situation/environment assessment, planning, detecting, verifying, diagnosing problems, aiding tactical and strategic decisions, and improving systems performance and utility*'. In this definition, we see the importance of situation awareness (useful data gathering) and situation assessment (decision making). The Information Fusion 2005 panel position paper [11] discussed various issues and challenges presented to our information fusion communities on how to determine situation assessment. In particular, different information fusion models were proposed to show the importance of processes. Blasch *et al.* [10] argued the importance of incorporating performance metrics for dynamic situation analysis in the information fusion process. Llinas [16] lists survivability and reliability as key *measures of effectiveness* (MOE) for tracking, communications, and information fusion. To that end, we explore techniques to further delineate the mathematical nature of these terms in a probabilistic manner. Additionally, Byington and Garga [17] proposed a *failure mode effects criticality analysis* (FMECA) for condition-based maintenance which was determined through multisensor fusion for predictive, preventative, and corrective maintenance. In this paper, we contend that the goal of situation awareness (whether it be a user, machine, or system) is situation assessment of one performance metric – survivability.

Clearly, the human is not only species on this earth that has information fusion processing capability to maintain survivability. Charles Darwin [15] pondered the issue of survivability between species' adaptation and environment changes in his famous evolution theory. He referred natural selection or *survival of the fittest* as a direct result from variations. In other words, the theory has suggested that the survivability of a system is directly related to the reconfigurability of the system due to situation assessment of the environment. Although many engineering damage control (survivable) applications or infrastructures are not biological in nature, they are still designed to survive harsh operation environments through system modifications. More likely, they are reconfigured when they cannot operate in their original forms as the environment changes. In these types of engineering analyses, Yoo and Smith [1] studied how soon a reliable system requires reconfiguration by using a term called *mean time between critical failures* (MTBCF). They did not address survivability in the paper, but they suggested the importance of reconfiguration to prevent system failure.

Net-centric operations require responsiveness to threats, vulnerabilities, and critical failures as well as methods to diagnose situational risks [14]. Monitoring, measuring and mitigating risk/threat are essential functions for fusion-system operations. *Risk* is the likelihood of a given threat attacking a particular

| Report Documentation Page | | | | | *Form Approved* *OMB No. 0704-0188* |
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| Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. | | | | | |
| 1. REPORT DATE **JUL 2007** | | 2. REPORT TYPE | | | 3. DATES COVERED **00-00-2007 to 00-00-2007** |
| 4. TITLE AND SUBTITLE **Survivability - An Information Fusion Process Metric from An Operational Perspective** | | | | | 5a. CONTRACT NUMBER |
| | | | | | 5b. GRANT NUMBER |
| | | | | | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | | | | | 5d. PROJECT NUMBER |
| | | | | | 5e. TASK NUMBER |
| | | | | | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory,2241 Avionics Circle,Wright Patterson AFB,OH,45433** | | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | | | | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | | | | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited** | | | | | |
| 13. SUPPLEMENTARY NOTES **10th International Conference on Information Fusion, 9-12 July 2007, Quebec, Canada.** | | | | | |
| 14. ABSTRACT **see report** | | | | | |
| 15. SUBJECT TERMS | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
| a. REPORT **unclassified** | b. ABSTRACT **unclassified** | c. THIS PAGE **unclassified** | **Same as Report (SAR)** | **8** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

vulnerability and the resulting impact. [12,13]. The goal of risk assessment as part of level 2/3 tacit fusion management is to enable individuals and systems to isolate separate risks and to identify potential mitigation options. The process of identifying risks can be objective process (such as part failures) and subjective process (such as adversarial actions). Selection of security controls based on cost, threat, and the degree of risk reduction are key to fusion system survivability.

Frank [2] showed an asymptotic expression of vulnerability analysis for a communication network. He extended the results in the survivability analysis [3], [4] for the command and control communication network. He explained the difficulty to evaluate survivability due to computation complexity. At the same time, he expressed the idea of computing survivability by using a term called *killability*. Later with a similar idea, Papanikolaou and Boulougouris [5] addressed design aspects of survivability for surface naval and merchant ships. They offered a mathematical formula showing how to compute survivability. According to their definition, the survivability *Ps* is calculated as

$$P_s = 1 - P_k = 1 - P_{su} P_v ,$$

where $P_k$ is the kill-ability, $P_{su}$ is the susceptibility and $P_v$ is the vulnerability. This formulation is very intuitive and a top down approach. Since large integrated systems often consist of many subsystems. such as power modules, communication modules, or computation modules, etc, they are not only susceptible for failure in the direction of threats, but also are affected by cascade failures from other interconnected subsystems. To calculate system's survivability, the system can first be divided into these smaller subsystems in terms of probability of susceptibility. The vulnerability of the system is directly dependent on the reliability of subsystems. As a result, the survivability formulation for a reconfigurable system becomes complex and difficult to be evaluated. Knight and Sullivan [6] presented a formal definition of the survivability of an information system, but the definition is more related to a fault tolerant system since they did not consider the system reconfiguablity in their survivability analysis. Varshney *et al.* [7] explained the difference between reliability and survivability in the context of *mean time between failures* (MTBF), however, the definition did not consider the system reconfiguration. To appropriately characterize survivability, Westmark [8] surveyed thousands of research papers regarding survivability, and concluded that there was a need for defining a proper computational survivability measure.

In this paper, we present a probabilistic approach to compute the survivability of a reconfigurable piping system. We chose a piping system because it balances the interplay between data (water), information management/routing (pumps), and hardware (machines). Defining a single aspect of information fusion between data, management, and infrastructure will require further analysis of a complex system. The piping system formulation shows the significant difference between the reliability and survivability analysis. We also extend/incorporate some of the existing reliability models [9] into our survivability analysis.

The rest of the paper is organized as follows. The main survivability ideas are presented in section 2. Simulation results are given in section 3. We conclude the paper in section 4.

## 2 System Survivability Analysis

To better understand the reliability and survivability analysis, we briefly describe several key reliability models.

***A. Reliability Models***

Typically, a reliable system has redundant components to sustain system function if a few components fail. For example, there are various studies on $k$-out-of-$n$:$G$ or $k$-out-of-$n$:$F$ systems, such as Kuo and Zuo [9]:

i) The $k$-out-of-$n$:$G$ system works (well) when at least $k$ components work among all $n$ components.
ii) The $k$-out-of-$n$:$F$ system fails when at least $k$ components can not function among all $n$ components.

These two systems are equivalent where a $k$-out-of-$n$:$G$ system is the same as a $(n-k+1)$-out-of-$n$:$F$ system. The reliability of a $k$-out-of-$n$:$G$ system is to compute the successful probability of the system. For example, we can calculate the reliability of a $k$-out-of-$n$:$G$ system with $n$ identical components whose successful probabilities are $p$ as,

$$R = \sum_{i=1}^{n} \binom{n}{i} p^i (1-p)^{n-i} ,$$

where $\binom{n}{i}$ is the combination that $n$ choose $i$. Also, the reliability model considers the uniform threat from all directions. In other words, a specific threat direction does not have any influence on the successful probability of the components in the reliability model, or the reliability stays the same regardless of where the threat is from.

***B. Survivability Models***

A survivable system is a reliable system with reconfiguration capability. To precisely define survivability, the initial form (or the original configuration) is an important factor which is also directly related to where the threat direction is from. The system can perform its functions by varying into a new form when it cannot survive in its original form through situation assessment. We define the survivability of a reconfigurable system as

$$S = R(f_0) + \sum_{i \neq 0} Q(f_0 \to f_i) A(f_i) R(f_i, c_i) \quad (1)$$

where $R(f_0)$ is the reliability of an initial configuration $f_0$ and $A(f_i)$ is probability of successful adaptation into a new configuration $f_i$. Since a system has to be fault tolerant, the configuration $f_0$ requires several redundant components in order to provide sufficient reliability. When threats come from different directions; we can compute reliability of each component by using total probability theorem as,

$$p(c) = \sum_j p(c \mid T_j) p(T_j)$$

where $T_j$ is the direction of a threat, $p(T_j)$ is *a-prior* probability of the threat, and $p(c|T_j)$ is conditional reliability of component $c$ based on a particular threat $T_j$. The component reliability can further be classified as a $k$-out-of-$n$:$G$ (good) system reliability metric shown as $R(f_0)$ and $R(f_i, c_i)$. This formulation includes the idea of susceptibility, reliability as well as adaptability for possible reconfiguration solutions. As shown in the formulation, there is a term $Q(f_0 \to f_i)$ that implies the system requires modification from its initial form.

Since the modification can occur under different circumstances, it can result in the following two types of survivability analysis: i) adaptation and ii) mutation.

i) Adaptation survivability refers to a system that reconfigures itself only when its initial form fails to work.
ii) Mutation survivability refers to a system that can reconfigure itself even when its initial form is still performing its tasks.

In our engineering analysis of survivability, we simply investigate the adaptation survivability of a system because many survivable engineering applications require a new configuration to sustain operations only when the initial form fails to work. During reconfiguration states, engineers and technicians can be dispatched to repair the failed components in their initial form. It is apparent that adaptation survivability is a more applicable analysis for engineering survivable systems.

***C. A Simple Survivable System***

First, we consider a simple survivable system shown in Figure 1 where the system has two pumps and only one can be operated due to a limited power supply. (This is analogous to a distributed sensor fusion system)

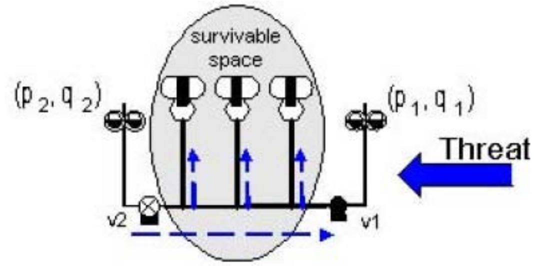


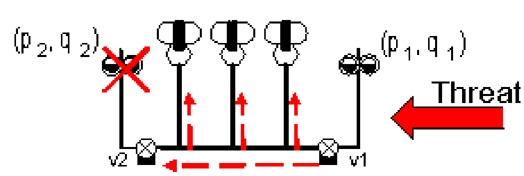

**Fig. 1**. Two Pumps System

In Figure 1 (as well as in subsequent figures), we use the symbol x (put the actual picture of a valve here) to indicate that a valve is closed, and o (picture) for an open valve. The pump supplies enough water to three sprinkler pipes in the middle segment of the system at any given time. We refer to the middle segment as the survivable space. In Figure 1, $p_i$ and $q_i$ denote the successful probability and the failure probability of the pumps 1 and 2. As we can see, the main threat is from the right hand-side of the system and we can assume that $p_1 < p_2$ where $p_i$ is the successful probability of the pump $i$. However, a reliable model will not consider the two pumps as being different because the system is unaware of where the threat is coming from. Rather, an initial form can be chosen to either operate pump 1 or operate pump 2. After the initial form is chosen to operate pump 1, the reliability is

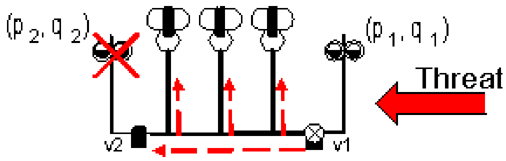
$$R = p_1,$$

or the reliability can become $p_2$ if pump 2 is operated in its initial form.

The values of $p_1$ and $p_2$ are highly dependant on where the threat is coming from. If a reliable and reconfigurable system can identify where the threat is coming from and reconfigure itself accordingly, the system becomes survivable. A better way is to operate the pump with the lower threat. In other words, the appropriate survivable system is to operate pump 2 and reconfigure itself to operate pump 1 if pump 2 fails. Here we have a survivable model with an initial form of operating a 1-out-of-1:G system for pump 2 with pump 1 as a backup. If pump 2 fails, there are four reconfiguration possibilities to open or close valve 1 and valve 2.




(a) Survivable Solution 1




(b) Survivable Solution 2

**Fig. 2.** Pumps Reconfiguration

Among them, two possibilities enable pump 1 to supply water flow to the sprinkler pipes as shown in Figure 2:

i) valve 1 is on and valve 2 is on,
ii) valve 1 is on and valve 2 is off.

Consequently, the system survivability is computed by using equation (1) as

$$S = R(f_0) + \sum_{i=1}^{2} Q(f_0 \to f_i) A(f_i) R(f_i, pump\,1)$$
$$= p_2 + q_2 \frac{2}{4} p_1 = p_2 + \frac{1}{2} p_1 q_2$$

where $q_2$ is the failure probability of pump 2. Conversely, we can define the nonsurvivability as

$$\overline{S} = \sum_{i \neq 0} Q(f_0 \to f_i)[A(f_i)Q(f_i, c_i) + \overline{A(f_i)}], \quad (2)$$

where $A(f_i)$ is the probability of successfully adaptation, $A(f_i)$ is the probability of failed adaptation, and $Q(f_i, c_i)$ is the failure probability of newly added components $c_i$ in the newly reconfigured form $f_i$. The definition is relatively easy to understand that

i) The term $Q(f_0 \to f_i)$ indicates the probability that a new form *fi* will be reconfigured.
ii) The term $A(f_i)Q(f_i, c_i)$ indicates that newly components $c_i$ fails to work in the new form $f_i$.
iii) The third term $\overline{A(f_i)}$ indicates that the system cannot be updated into a new form $f_i$.

These conditions all produce a system without survivable options. We can use the same idea to compute the nonsurvivability of the current system when pump 2 fails to work. There are two situations:

i) valve 1 is on but pump 1 fails, and
ii) valve 1 cannot be turned on.

In both conditions, we can use equation (2) to calculate the nonsurvivability as,

$$\overline{S} = q_2 \left( \frac{1}{2} q_1 + \frac{1}{2} \right).$$

Interesting enough, we can also verify that the sum of the survivability and nonsurvivability is unity, or

$$S + \overline{S} = p_2 + \frac{1}{2} q_2 p_1 + q_2 \left( \frac{1}{2} q_1 + \frac{1}{2} \right) = 1.$$

In the current system, we can easily see that $S > R$. It implies that a survivable system can have a higher successful probability than a reliable system. The survivable system is capable of configuring an initial form depending on where the threat is coming from, and it can reconfigure itself to avoid failures. If the system cannot identify where the threat is coming from, its survivability will be degraded. For the same system shown in Figure 1, the survivability of the system when it can identify the threat correctly is

$$S = p_2 + \frac{1}{2} p_1 q_2$$

We can compare it with another system that identifies the threat as coming from the wrong direction, or the system operates pump 1 in its initial form. The survivability of such a system is

$$\tilde{S} = p_1 + \frac{1}{2} p_2 q_1$$

Clearly, we can calculate

$$S - \tilde{S} = \left( p_2 + \frac{1}{2} p_1 q_2 \right) - \left( p_1 + \frac{1}{2} p_2 q_1 \right)$$
$$= \frac{3}{2} (p_2 - p_1) \geq 0.$$

More precisely, we prove that $S \geq \tilde{S}$. This result suggests that a reconfigurable system is more survivable if its initial form is determined by avoiding the threat. In other words, a threat awareness (or situation awareness) and reconfigurable system has a clear advantage in terms of better survivability. Mathematically, we show that a reconfigurable system has better survivability if the system has threat awareness capability. Nonetheless, we demonstrate the difference between the survivability and reliability analysis.

### *D. A More Complex Three Pumps System*

We study another more complex survivable system with three pumps as shown in Figure 3. The system is capable of operating two pumps simultaneously.

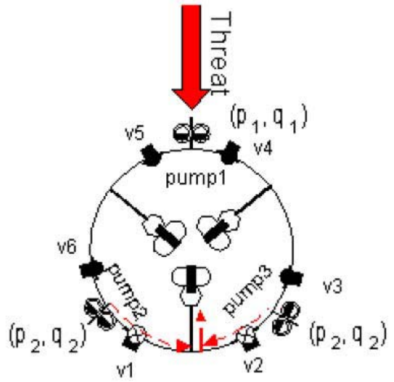



**Fig. 3.** Three Pumps System

As indicated in the figure, the main threat is from the direction of the pump 1. A viable initial form $f_0$ is to operate pump 2 and pump 3. Two pumps supply water flow into the sprinkler pipes as valves 1 and 2 are switched on. Accordingly, there are two possible operation modes for pumps 2 and 3:

i) *2*-out-of-*2*:*G* with 1 backup system and
ii) *1*-out-of-*2*:*G* with 1 backup system.

We consider the adaptation survivability where the system reconfigures itself only when its initial form fails to work.

***Mode I: a 2-out-of-2:G with 1 backup system:***
In this mode, the system works when both pumps (pumps 2 and 3) are operating. The reliability of the initial form $f_0$ is

$$R(f_0) = p_2^2 .$$

If either pump 2 or pump 3 fails, the system must reconfigure itself to operate pump 1 for the survivable mission. However, if both pumps 2 and 3 fail, the result will be that the system is unable to operate. If either pump fails, there are two survivable forms:

i) form $f_1$ that requires pumps 1 and 3 to work when pump 2 fails, and
ii) form $f_2$ that requires pumps 1 and 2 to work when pump 3 fails.

The new form $f_1$ is shown in Figure 4.

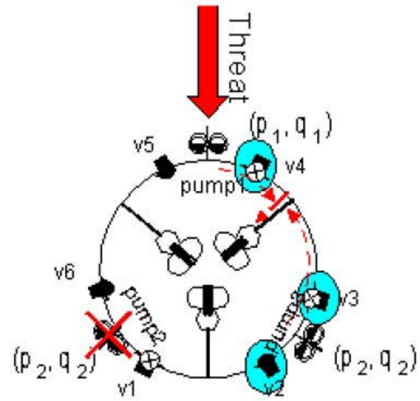



**Fig. 4**. Reconfiguration of Three Pumps System

It suggests that

$$Q(f_0 \to f_1) = p_2 q_2 .$$

To survive by using form $f_1$, the following adaptation conditions are required in addition to pump 1 being in successful operation:

i) valve 2 is off, and
ii) valve 3 and valve 4 are on.

It implies that $A(f_1) = \frac{1}{8}$ because there is one eighth of the probability that the corresponding valves are switched into the correct states. Also, the reliability of the new form depends on the successful probability of pump 1, or $R(f_1, pump1) = p_1$. Similarly, we can compute the probability for form $f_2$ to sustain survivable functions. Hence, the survivability of this system is

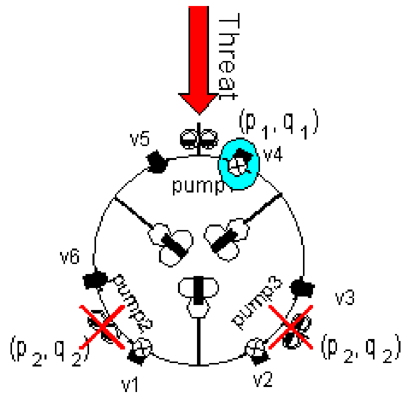
$$S = R(f_0) + \sum_{i=1}^{2} Q(f_0 \to f_i) A(f_i) R(f_i, pump\,1)$$
$$= p_2^2 + 2\left( p_2 q_2 \frac{1}{8} p_1 \right) = p_2^2 + \frac{1}{4} p_1 p_2 q_2 .$$

We can also note that we did not compute the survivable form in which both pumps 2 and 3 fail. In this form, the system cannot survive because the system is operated in the *2*-out-of-*2*:*G* model. When both pumps fail, there is no possibility of operating one pump to sustain the survivable function.

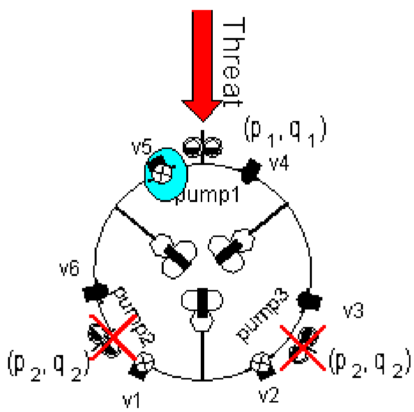
***Mode II: a 1-out-of-2:G with 1 backup system:***
This mode is operated a little differently than the previous mode. The system works when either pump (pump 2 or pump 3) or both pumps (pumps 2 and 3) are working. The reliability of the initial form $f_0$ is

$$R(f_0) = p_2^2 + 2 p_2 q_2 .$$

Unlike the previous mode, the system requires new configurations only when both pumps 2 and 3 fail to work. The system will reconfigure when both pump 2 and pump 3 fail. There are two new forms as shown in Figures 5(a) and 5(b),




(a) Survivable Solution 1




(b) Survivable Solution 2

**Fig. 5**. Three Pumps Reconfiguration

i) form $f_1$ that requires pump 1 to work and valve 4 to be on, and
ii) form $f_2$ that requires pump 1 to work and valve 5 to be on.

It implies that $Q(f_0 \to f_1) = Q(f_0 \to f_2) = q_2^2$ and $A(f_1) = A(f_2) = \frac{1}{2}$ because there is one half of the probability that the corresponding valves are switched into the correct states. Also, the reliability of the new form is depended on the successful probability of pump 1, or $R(f_1, pump1) = R(f_2, pump1) = p_1$. Consequentially, the survivability of this system is

$$S = R(f_0) + \sum_{i=1}^{2} Q(f_0 \to f_i)A(f_i)R(f_i, pump\,1)$$
$$= p_2^2 + 2p_2q_2 + 2\left(q_2^2 \frac{1}{2} p_1\right) = p_2^2 + 2p_2q_2 + p_1q_2^2.$$

Intuitively, we know that mode II has better survivability than mode I. In mathematics, it can also be validated in the survivability results computed from both modes. We can extend the system into a more general form. The system is a $k$-out-of-$n$:$G$ model with $m$ backup components. There can be various situations that we can use to compute the survivability of such a system. However, the adaptation depends highly on the design of topology or arrangements of system components. In this paper, we have considered two topologies:

i) line topology and
ii) ring topology.

This paper is not focused on determining which topology is a better survivable design, but it shows the significance of design which can highly influence the system's survivability. Also, we demonstrate the importance of survivability in situation assessment. When an information fusion process utilizes survivability as the performance metric, situation awareness becomes more important to gather useful data for sustaining the system's successful operation.

# 3 Simulations

For the examples presented, we were interested in the effects for the 3-pump system configurations representing either the communications data router for a distributed fusion system.

Example 1: ***a 2-out-of-2:G with 1 backup system***
In this example, we consider the recovery of a system due to a failure in a single communication channel.

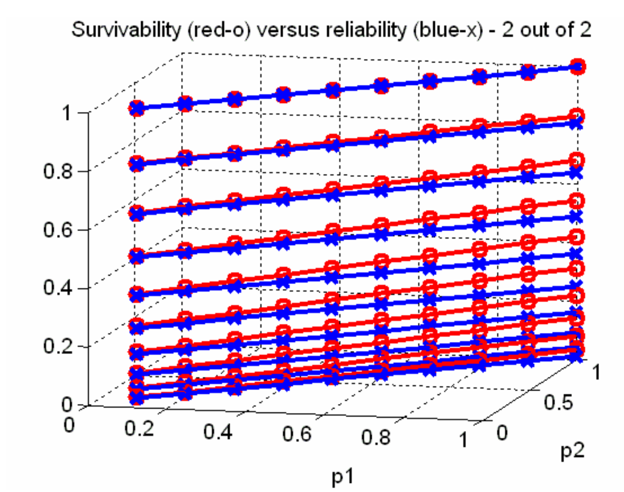



**Fig. 6**. A 2-out-of-2:G with 1 backup system

From the simulation, we see that the survivability (red dashed o) and the reliability (blue dashed x) in Figure 6. The survivability and reliability are almost the same in the performance evaluation, but the survivability can be seen clearly better than the reliability metric as the components become more and more reliable. It strongly suggests that a reconfigurable system has better performance measure compared to a system without reconfiguration capability.

Example 2: ***a 1-out-of-2:G with 1 backup system:***
Here, we simulate the ability of a fusion system with the capability to recover from threats, breakdowns, and other processing errors in a 1-out-of-2:G system. The simulation result is shown in Figure 7.

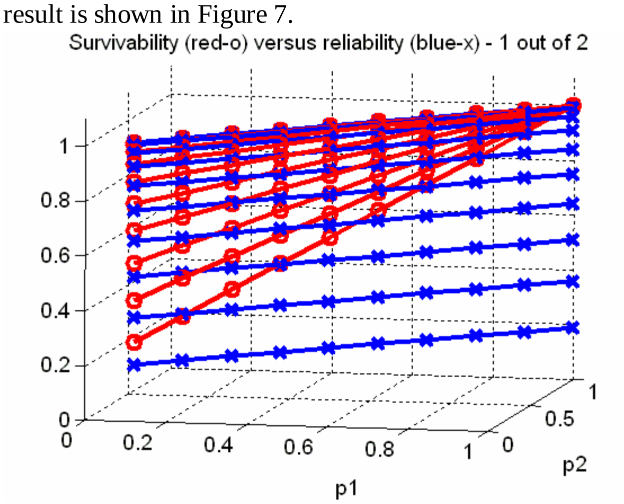



**Fig. 7**. A 1-out-of-2:G with 1 backup system

In this simulation of a fusion system, we see that reliability (blue dashed x) performs at much of a constant rate wherein all data is needed in a distributed fusion system to conclude performance. However, the survivability (red dashed o) shows that the system will be operable with many opportunities for data transmission. Also, the survivability metrics outperform reliability. It further suggested that a reconfigurable system has better performance measure.

## 4 Conclusion

In this paper, we present a mathematical description for survivability analysis, and show its similarities and differences to reliability analysis. A survivable system is a reliable system which has reconfiguration capability. Its survivability is dependant on i) the system design and ii) ability to identify threats. In other words, a survivable system must be able to determine an initial form from the arrangements of its components and the direction of the threat. We consider a pipe system whose valves can be turned into two states: i) on and ii) off with equal probabilities. This assumption is used to simplify our analysis. We can use a more complex model of the valves to study the survivability of a similar piping system. This study could potentially be used to analyze other systems' survivability such as power network systems, computer network systems, military reconfigurable information systems, and other large reconfigurable network systems. Their fundamental frameworks are the systems' capability to assess survivability and dynamically aware of the situation changes. Consequently, we can generalize these systems in the same framework and investigate their survivability in the exactly same context. More importantly, we contended survivability is a better performance metric for an information process for situation assessment.

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